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S. S. Adler

*Brookhaven National Laboratory*

Sergey Belikov

*Iowa State University*

S. Bhagavatula

*Iowa State University*

Paul Constantin

*Iowa State University*

Nathan C. Grau

*Iowa State University*

*See next page for additional authors*

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# Measurement of identified $\pi(0)$ and inclusive photon second-harmonic parameter $v(2)$ and implications for direct photon production in $\sqrt{s}(\text{NN})=200$ GeV

## Abstract

The azimuthal distribution of identified  $\pi(0)$  and inclusive photons has been measured in  $\sqrt{s}(\text{NN})=200$  GeV Au+Au collisions with the PHENIX experiment at the Relativistic Heavy-Ion Collider (RHIC). The second-harmonic parameter ( $v(2)$ ) was measured to describe the observed anisotropy of the azimuthal distribution. The measured inclusive photon  $v(2)$  is consistent with the value expected for the photons from hadron decay and is also consistent with the lack of direct photon signal over the measured  $p(T)$  range 1-6 GeV/c. An attempt is made to extract  $v(2)$  of direct photons.

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## Comments

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## Authors

S. S. Adler, Sergey Belikov, S. Bhagavatula, Paul Constantin, Nathan C. Grau, John C. Hill, John G. Lajoie, Alexandre Lebedev, Craig Ogilvie, Jan Rak, Marzia Rosati, F. K. Wohn, et al., and PHENIX Collaboration

# Measurement of Identified $\pi^0$ and Inclusive Photon Second-Harmonic Parameter $v_2$ and Implications for Direct Photon Production in $\sqrt{s_{NN}} = 200$ GeV Au + Au

S. S. Adler,<sup>5</sup> S. Afanasiev,<sup>17</sup> C. Aidala,<sup>5</sup> N. N. Ajitanand,<sup>43</sup> Y. Akiba,<sup>20,38</sup> J. Alexander,<sup>43</sup> R. Amirikas,<sup>12</sup> L. Aphecetche,<sup>45</sup> S. H. Aronson,<sup>5</sup> R. Auerbeck,<sup>44</sup> T. C. Awes,<sup>35</sup> R. Azmoun,<sup>44</sup> V. Babintsev,<sup>15</sup> A. Baldissieri,<sup>10</sup> K. N. Barish,<sup>6</sup> P. D. Barnes,<sup>27</sup> B. Bassalleck,<sup>33</sup> S. Bathe,<sup>30</sup> S. Batsouli,<sup>9</sup> V. Baublis,<sup>37</sup> A. Bazilevsky,<sup>39,15</sup> S. Belikov,<sup>16,15</sup> Y. Berdnikov,<sup>40</sup> S. Bhagavatula,<sup>16</sup> J. G. Boissevain,<sup>27</sup> H. Borel,<sup>10</sup> S. Borenstein,<sup>25</sup> M. L. Brooks,<sup>27</sup> D. S. Brown,<sup>34</sup> N. Bruner,<sup>33</sup> D. Bucher,<sup>30</sup> H. Buesching,<sup>30</sup> V. Bumazhnov,<sup>15</sup> G. Bunce,<sup>5,39</sup> J. M. Burward-Hoy,<sup>26,44</sup> S. Butsyk,<sup>44</sup> X. Camard,<sup>45</sup> J.-S. Chai,<sup>18</sup> P. Chand,<sup>4</sup> W. C. Chang,<sup>2</sup> S. Chernichenko,<sup>15</sup> C. Y. Chi,<sup>9</sup> J. Chiba,<sup>20</sup> M. Chiu,<sup>9</sup> I. J. Choi,<sup>52</sup> J. Choi,<sup>19</sup> R. K. Choudhury,<sup>4</sup> T. Chujo,<sup>5</sup> V. Cianciolo,<sup>35</sup> Y. Cobigo,<sup>10</sup> B. A. Cole,<sup>9</sup> P. Constantin,<sup>16</sup> D. d'Enterria,<sup>45</sup> G. David,<sup>5</sup> H. Delagrange,<sup>45</sup> A. Denisov,<sup>15</sup> A. Deshpande,<sup>39</sup> E. J. Desmond,<sup>5</sup> A. Devismes,<sup>44</sup> O. Dietzsch,<sup>41</sup> O. Drapier,<sup>25</sup> A. Drees,<sup>44</sup> R. du Rietz,<sup>29</sup> A. Durum,<sup>15</sup> D. Dutta,<sup>4</sup> Y. V. Efremenko,<sup>35</sup> K. El Chenawi,<sup>49</sup> A. Enokizono,<sup>14</sup> H. En'yo,<sup>38,39</sup> S. Esumi,<sup>48</sup> L. Ewell,<sup>5</sup> D. E. Fields,<sup>33,39</sup> F. Fleuret,<sup>25</sup> S. L. Fokin,<sup>23</sup> B. D. Fox,<sup>39</sup> Z. Fraenkel,<sup>51</sup> J. E. Frantz,<sup>9</sup> A. Franz,<sup>5</sup> A. D. Frawley,<sup>12</sup> S.-Y. Fung,<sup>6</sup> S. Garpman,<sup>29,\*</sup> T. K. Ghosh,<sup>49</sup> A. Glenn,<sup>46</sup> G. Gogiberidze,<sup>46</sup> M. Gonin,<sup>25</sup> J. Gosset,<sup>10</sup> Y. Goto,<sup>39</sup> R. Granier de Cassagnac,<sup>25</sup> N. Grau,<sup>16</sup> S. V. Greene,<sup>49</sup> M. Grosse Perdekamp,<sup>39</sup> W. Guryn,<sup>5</sup> H.-Å. Gustafsson,<sup>29</sup> T. Hachiya,<sup>14</sup> J. S. Haggerty,<sup>5</sup> H. Hamagaki,<sup>8</sup> A. G. Hansen,<sup>27</sup> E. P. Hartouni,<sup>26</sup> M. Harvey,<sup>5</sup> R. Hayano,<sup>8</sup> N. Hayashi,<sup>38</sup> X. He,<sup>13</sup> M. Heffner,<sup>26</sup> T. K. Hemmick,<sup>44</sup> J. M. Heuser,<sup>44</sup> M. Hibino,<sup>50</sup> J. C. Hill,<sup>16</sup> W. Holzmann,<sup>43</sup> K. Homma,<sup>14</sup> B. Hong,<sup>22</sup> A. Hoover,<sup>34</sup> T. Ichihara,<sup>38,39</sup> V. V. Ikonnikov,<sup>23</sup> K. Imai,<sup>24,38</sup> D. Isenhower,<sup>1</sup> M. Ishihara,<sup>38</sup> M. Issah,<sup>43</sup> A. Isupov,<sup>17</sup> B. V. Jacak,<sup>44</sup> W. Y. Jang,<sup>22</sup> Y. Jeong,<sup>19</sup> J. Jia,<sup>44</sup> O. Jinnouchi,<sup>38</sup> B. M. Johnson,<sup>5</sup> S. C. Johnson,<sup>26</sup> K. S. Joo,<sup>31</sup> D. Jouan,<sup>36</sup> S. Kametani,<sup>8,50</sup> N. Kamihara,<sup>47,38</sup> M. Kaneta,<sup>39</sup> J. H. Kang,<sup>52</sup> S. S. Kapoor,<sup>4</sup> K. Katou,<sup>50</sup> S. Kelly,<sup>9</sup> B. Khachaturov,<sup>51</sup> A. Khanzadeev,<sup>37</sup> J. Kikuchi,<sup>50</sup> D. H. Kim,<sup>31</sup> D. J. Kim,<sup>52</sup> D. W. Kim,<sup>19</sup> E. Kim,<sup>42</sup> G.-B. Kim,<sup>25</sup> H. J. Kim,<sup>52</sup> E. Kistenev,<sup>5</sup> A. Kiyomichi,<sup>48</sup> K. Kiyoyama,<sup>32</sup> C. Klein-Boesing,<sup>30</sup> H. Kobayashi,<sup>38,39</sup> L. Kochenda,<sup>37</sup> V. Kochetkov,<sup>15</sup> D. Koehler,<sup>33</sup> T. Kohama,<sup>14</sup> M. Kopytine,<sup>44</sup> D. Kotchetkov,<sup>6</sup> A. Kozlov,<sup>51</sup> P. J. Kroon,<sup>5</sup> C. H. Kuberg,<sup>1,27</sup> K. Kurita,<sup>39</sup> Y. Kuroki,<sup>48</sup> M. J. Kweon,<sup>22</sup> Y. Kwon,<sup>52</sup> G. S. Kyle,<sup>34</sup> R. Lacey,<sup>43</sup> V. Ladygin,<sup>17</sup> J. G. Lajoie,<sup>16</sup> A. Lebedev,<sup>16,23</sup> S. Leckey,<sup>44</sup> D. M. Lee,<sup>27</sup> S. Lee,<sup>19</sup> M. J. Leitch,<sup>27</sup> X. H. Li,<sup>6</sup> H. Lim,<sup>42</sup> A. Litvinenko,<sup>17</sup> M. X. Liu,<sup>27</sup> Y. Liu,<sup>36</sup> C. F. Maguire,<sup>49</sup> Y. I. Makdisi,<sup>5</sup> A. Malakhov,<sup>17</sup> V. I. Manko,<sup>23</sup> Y. Mao,<sup>7,38</sup> G. Martinez,<sup>45</sup> M. D. Marx,<sup>44</sup> H. Masui,<sup>48</sup> F. Matathias,<sup>44</sup> T. Matsumoto,<sup>8,50</sup> P. L. McGaughey,<sup>27</sup> E. Melnikov,<sup>15</sup> F. Messer,<sup>44</sup> Y. Miake,<sup>48</sup> J. Milan,<sup>43</sup> T. E. Miller,<sup>49</sup> A. Milov,<sup>44,51</sup> S. Mioduszewski,<sup>5</sup> R. E. Mischke,<sup>27</sup> G. C. Mishra,<sup>13</sup> J. T. Mitchell,<sup>5</sup> A. K. Mohanty,<sup>4</sup> D. P. Morrison,<sup>5</sup> J. M. Moss,<sup>27</sup> F. Mühlbacher,<sup>44</sup> D. Mukhopadhyay,<sup>51</sup> M. Muniruzzaman,<sup>6</sup> J. Murata,<sup>38,39</sup> S. Nagamiya,<sup>20</sup> J. L. Nagle,<sup>9</sup> T. Nakamura,<sup>14</sup> B. K. Nandi,<sup>6</sup> M. Nara,<sup>48</sup> J. Newby,<sup>46</sup> P. Nilsson,<sup>29</sup> A. S. Nyanin,<sup>23</sup> J. Nystrand,<sup>29</sup> E. O'Brien,<sup>5</sup> C. A. Ogilvie,<sup>16</sup> H. Ohnishi,<sup>5,38</sup> I. D. Ojha,<sup>49,3</sup> K. Okada,<sup>38</sup> M. Ono,<sup>48</sup> V. Onuchin,<sup>15</sup> A. Oskarsson,<sup>29</sup> I. Otterlund,<sup>29</sup> K. Oyama,<sup>8</sup> K. Ozawa,<sup>8</sup> D. Pal,<sup>51</sup> A. P. T. Palounek,<sup>27</sup> V. Pantuev,<sup>44</sup> V. Papavassiliou,<sup>34</sup> J. Park,<sup>42</sup> A. Parmar,<sup>33</sup> S. F. Pate,<sup>34</sup> T. Peitzmann,<sup>30</sup> J.-C. Peng,<sup>27</sup> V. Peresedov,<sup>17</sup> C. Pinkenburg,<sup>5</sup> R. P. Pisani,<sup>5</sup> F. Plasil,<sup>35</sup> M. L. Purschke,<sup>5</sup> A. K. Purwar,<sup>44</sup> J. Rak,<sup>16</sup> I. Ravinovich,<sup>51</sup> K. F. Read,<sup>35,46</sup> M. Reuter,<sup>44</sup> K. Reygers,<sup>30</sup> V. Riabov,<sup>37,40</sup> Y. Riabov,<sup>37</sup> G. Roche,<sup>28</sup> A. Romana,<sup>25</sup> M. Rosati,<sup>16</sup> P. Rosnet,<sup>28</sup> S. S. Ryu,<sup>52</sup> M. E. Sadler,<sup>1</sup> N. Saito,<sup>38,39</sup> T. Sakaguchi,<sup>8,50</sup> M. Sakai,<sup>32</sup> S. Sakai,<sup>48</sup> V. Samsonov,<sup>37</sup> L. Sanfratello,<sup>33</sup> R. Santo,<sup>30</sup> H. D. Sato,<sup>24,38</sup> S. Sato,<sup>5,48</sup> S. Sawada,<sup>20</sup> Y. Schutz,<sup>45</sup> V. Semenov,<sup>15</sup> R. Seto,<sup>6</sup> M. R. Shaw,<sup>1,27</sup> T. K. Shea,<sup>5</sup> T.-A. Shibata,<sup>47,38</sup> K. Shigaki,<sup>14,20</sup> T. Shiina,<sup>27</sup> C. L. Silva,<sup>41</sup> D. Silvermyr,<sup>27,29</sup> K. S. Sim,<sup>22</sup> C. P. Singh,<sup>3</sup> V. Singh,<sup>3</sup> M. Sivertz,<sup>5</sup> A. Soldatov,<sup>15</sup> R. A. Soltz,<sup>26</sup> W. E. Sondheim,<sup>27</sup> S. P. Sorensen,<sup>46</sup> I. V. Sourikova,<sup>5</sup> F. Staley,<sup>10</sup> P. W. Stankus,<sup>35</sup> E. Stenlund,<sup>29</sup> M. Stepanov,<sup>34</sup> A. Ster,<sup>21</sup> S. P. Stoll,<sup>5</sup> T. Sugitate,<sup>14</sup> J. P. Sullivan,<sup>27</sup> E. M. Takagui,<sup>41</sup> A. Taketani,<sup>38,39</sup> M. Tamai,<sup>50</sup> K. H. Tanaka,<sup>20</sup> Y. Tanaka,<sup>32</sup> K. Tanida,<sup>38</sup> M. J. Tannenbaum,<sup>5</sup> P. Tarján,<sup>11</sup> J. D. Tepe,<sup>1,27</sup> T. L. Thomas,<sup>33</sup> J. Tojo,<sup>24,38</sup> H. Torii,<sup>24,38</sup> R. S. Towell,<sup>1</sup> I. Tserruya,<sup>51</sup> H. Tsuruoka,<sup>48</sup> S. K. Tuli,<sup>3</sup> H. Tydesjö,<sup>29</sup> N. Tyurin,<sup>15</sup> H. W. van Hecke,<sup>27</sup> J. Velkovska,<sup>5,44</sup> M. Velkovsky,<sup>44</sup> V. Veszprémi,<sup>11</sup> L. Villatte,<sup>46</sup> A. A. Vinogradov,<sup>23</sup> M. A. Volkov,<sup>23</sup> E. Vznuzdaev,<sup>37</sup> X. R. Wang,<sup>13</sup> Y. Watanabe,<sup>38,39</sup> S. N. White,<sup>5</sup> F. K. Wohn,<sup>16</sup> C. L. Woody,<sup>5</sup> W. Xie,<sup>6</sup> Y. Yang,<sup>7</sup> A. Yanovich,<sup>15</sup> S. Yokkaichi,<sup>38,39</sup> G. R. Young,<sup>35</sup> I. E. Yushmanov,<sup>23</sup> W. A. Zajc,<sup>9,†</sup> C. Zhang,<sup>9</sup> S. Zhou,<sup>7</sup> S. J. Zhou,<sup>51</sup> and L. Zolin<sup>17</sup>

(PHENIX Collaboration)

<sup>1</sup>Abilene Christian University, Abilene, Texas 79699, USA<sup>2</sup>Institute of Physics, Academia Sinica, Taipei 11529, Taiwan<sup>3</sup>Department of Physics, Banaras Hindu University, Varanasi 221005, India

- <sup>4</sup>Bhabha Atomic Research Centre, Bombay 400 085, India  
<sup>5</sup>Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>6</sup>University of California - Riverside, Riverside, California 92521, USA  
<sup>7</sup>China Institute of Atomic Energy (CIAE), Beijing, People's Republic of China  
<sup>8</sup>Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan  
<sup>9</sup>Columbia University, New York, New York 10027, USA  
and Nevis Laboratories, Irvington, New York 10533, USA  
<sup>10</sup>Dapnia, CEA Saclay, F-91191, Gif-sur-Yvette, France  
<sup>11</sup>Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary  
<sup>12</sup>Florida State University, Tallahassee, Florida 32306, USA  
<sup>13</sup>Georgia State University, Atlanta, Georgia 30303, USA  
<sup>14</sup>Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan  
<sup>15</sup>IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia  
<sup>16</sup>Iowa State University, Ames, Iowa 50011, USA  
<sup>17</sup>Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia  
<sup>18</sup>KAERI, Cyclotron Application Laboratory, Seoul, South Korea  
<sup>19</sup>Kangnung National University, Kangnung 210-702, South Korea  
<sup>20</sup>KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan  
<sup>21</sup>KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences (MTA KFKI RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary  
<sup>22</sup>Korea University, Seoul, 136-701, Korea  
<sup>23</sup>Russian Research Center "Kurchatov Institute", Moscow, Russia  
<sup>24</sup>Kyoto University, Kyoto 606-8502, Japan  
<sup>25</sup>Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France  
<sup>26</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA  
<sup>27</sup>Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA  
<sup>28</sup>LPC, Université Blaise Pascal, CNRS-IN2P3, Clermont-Fd, 63177 Aubiere Cedex, France  
<sup>29</sup>Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden  
<sup>30</sup>Institut für Kernphysik, University of Muenster, D-48149 Muenster, Germany  
<sup>31</sup>Myongji University, Yongin, Kyonggido 449-728, Korea  
<sup>32</sup>Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan  
<sup>33</sup>University of New Mexico, Albuquerque, New Mexico 87131, USA  
<sup>34</sup>New Mexico State University, Las Cruces, New Mexico 88003, USA  
<sup>35</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA  
<sup>36</sup>IPN-Orsay, Université Paris Sud, CNRS-IN2P3, Boîte Postale 1, F-91406, Orsay, France  
<sup>37</sup>PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia  
<sup>38</sup>RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan  
<sup>39</sup>RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>40</sup>Saint Petersburg State Polytechnic University, St. Petersburg, Russia  
<sup>41</sup>Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil  
<sup>42</sup>System Electronics Laboratory, Seoul National University, Seoul, South Korea  
<sup>43</sup>Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA  
<sup>44</sup>Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794, USA  
<sup>45</sup>SUBATECH, Ecole des Mines de Nantes, CNRS-IN2P3, Université de Nantes Boîte Postale 20722 - 44307, Nantes, France  
<sup>46</sup>University of Tennessee, Knoxville, Tennessee 37996, USA  
<sup>47</sup>Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan  
<sup>48</sup>Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan  
<sup>49</sup>Vanderbilt University, Nashville, Tennessee 37235, USA  
<sup>50</sup>Waseda University, Advanced Research Institute for Science and Engineering, 17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan  
<sup>51</sup>Weizmann Institute, Rehovot 76100, Israel  
<sup>52</sup>Yonsei University, IPAP, Seoul 120-749, Korea

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The azimuthal distribution of identified  $\pi^0$  and inclusive photons has been measured in  $\sqrt{s_{NN}} = 200$  GeV Au + Au collisions with the PHENIX experiment at the Relativistic Heavy-Ion Collider (RHIC). The second-harmonic parameter ( $v_2$ ) was measured to describe the observed anisotropy of the azimuthal distribution. The measured inclusive photon  $v_2$  is consistent with the value expected for the photons from hadron decay and is also consistent with the lack of direct photon signal over the measured  $p_T$  range 1–6 GeV/c. An attempt is made to extract  $v_2$  of direct photons.

Among the most exciting features of the experimental data from the Relativistic Heavy-Ion Collider (RHIC) are the suppression of high  $p_T$  hadron yields [1–5], the baryon excess at intermediate  $p_T$  [6–9], and the quark number scaling of the identified hadron  $v_2$  [10,11]. Theoretically, the observed high  $p_T$  suppression has been attributed to energy loss of the hard-scattered partons [12,13]. Experimentally, the absence of the suppression in  $d + \text{Au}$  collisions has shown that it is a final-state effect due to the hot and dense matter created in central Au + Au collisions [14–17]. The quark number scaling of the measured elliptic flow parameter  $v_2$  and the nuclear modification factor  $R_{\text{cp}}$  of baryons versus mesons may suggest the existence of a thermalized partonic phase before hadronization [18,19].

The second-harmonic coefficient parameter  $v_2$  of the azimuthal distribution of the particles produced in heavy-ion collisions is defined by

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Phi_{\text{RP}})], \quad (1)$$

where  $\phi$  is the azimuthal direction of the particle and  $\Phi_{\text{RP}}$  is the direction of the nuclear impact parameter (reaction plane) in a given collision. The  $v_2$  in high-energy heavy-ion collisions is considered to be sensitive to the initial geometric overlap of the colliding nuclei as well as the later expansion driven by the initial pressure. Theoretically, the dominant source of  $v_2$  at low  $p_T$  is the expansion of the dense matter in the direction of the short axis of the overlap zone, and at high  $p_T$  is the parton energy loss given by the shape of the geometrical overlap. The quark coalescence (recombination) might be responsible for the  $v_2$  in the intermediate  $p_T$  region. However, the experimental definition of  $v_2$  includes any second-harmonic correlation with respect to the event plane, which is given by the beam direction and the impact parameter direction. Detailed  $v_2$  measurements of identified particles at higher  $p_T$  than 2 GeV/ $c$ , where hydrodynamics alone does not describe the measurements, would enable us to understand the different mechanisms that generate  $v_2$  and to investigate the transition region from low to high  $p_T$ . Especially, the  $v_2$  of identified  $\pi^0$  will give a baseline measurement of inclusive photon  $v_2$  to extract the direct photon  $v_2$ .

The direct photons produced in hard scattering are penetrating probes of the produced dense matter in heavy-ion collisions. Recently, we observed that the centrality dependence of the direct photon yield in  $\sqrt{s_{\text{NN}}} = 200$  GeV Au + Au collisions is consistent with binary collision scaling [20]. The lack of suppression of direct photons is further evidence in favor of the final-state effect in hadron suppression. In addition to the initially produced hard photons that should inherently follow binary scaling, there may be other counteracting effects resulting in apparent binary scaling. For example, some fraction of the photons may originate from partons having experienced energy

loss, causing an analogous suppression of these photons [21] similar to hadrons. On the other hand, the parton energy loss may enhance the photon yield via bremsstrahlung while passing through the hot and dense matter [22]. The thermal emission of photons radiated from the hot and dense matter is also expected to increase direct photon yield for central Au + Au collisions [23].

The  $v_2$  measurement of the direct photons could help to confirm that the observed binary scaling of the direct photon excess is attributable to the direct photon production being dominated by the initial hard scattering. The  $v_2$  measurement of the direct photons would give additional and complementary information to help disentangle the various scenarios of direct photon production, as well as to provide more information on the dynamics and properties of the produced hot and dense matter. The  $v_2$  of photons from the initial Compton-like hard scattering is expected to be zero if they do not interact with the hot and dense matter produced during the collision. However, when the  $v_2$  of high  $p_T$  hadrons is given purely by the parton energy loss, the photons from the parton fragmentation outside of the reaction zone should have  $v_2$  similar to the hadrons at high  $p_T$ . Such photon fraction is expected to be about 50% of total direct photon yield at 3.5 GeV/ $c$  in  $p_T$  [21,22]. On the other hand, one would expect that the photons originating from bremsstrahlung due to the passage of partons through the hot and dense matter should have the opposite (negative) sign in  $v_2$  compared with hadrons, because the parton energy loss is larger in the long axis of the overlapping region (out-of-plane). Finally, the photons from the thermal radiation should reflect the dynamical evolution of the produced hot and dense matter. There are recent theoretical predictions for different mechanisms [24].

In this Letter we present measurements of the  $v_2$  of  $\pi^0$  and inclusive  $\gamma$ , as a function of transverse momentum and collision centrality, and we discuss the implications for the yield and  $v_2$  of direct photons. The data are for 200 GeV Au + Au collisions from the PHENIX experiment [25] recorded during Run 2 at RHIC. The event trigger and centrality definition are given by the beam-beam counters (BBCs) and the zero degree calorimeters (ZDCs). The number of charged particles measured with the BBCs and the neutral spectators measured with the ZDCs are correlated with the number of participating nucleons, thus together providing a measure of the centrality. The event plane, which is a measure of reaction plane, is determined using the two BBCs at  $|\eta| = 3.1 \sim 3.9$ , where each counter consists of 64 photomultiplier tubes (PMTs) with quartz Cherenkov radiators in front, surrounding the beam pipe. The elliptic axis of the event plane  $\Phi_{\text{measured}}$  is calculated by the angle weighted with the PMT amplitude using the second-harmonic moment as described in Refs. [10,26]. The measured event anisotropy is corrected for a finite resolution of the measured event plane. The

estimated event plane resolution  $\sigma_{RP} = \langle \cos[2(\Phi_{\text{measured}} - \Phi_{RP})] \rangle$  is 0.3 on average, with a maximum of  $\sim 0.4$  in the midcentral collisions. The corrected  $v_2$  is calculated via the formula  $v_2 = \langle \cos[2(\phi - \Phi_{\text{measured}})] \rangle / \sigma_{RP}$ . The phase space used for the determination of the event plane for this analysis is 3–4 units away from the midrapidity, while the inclusive photon and the identified  $\pi^0$  are measured at  $|\eta| < 0.35$ .

The photon identification and the  $\pi^0$  reconstruction are performed in the same way as presented elsewhere [4]. The photon candidate clusters for both inclusive photon and  $\pi^0$  measurement are first selected by their times of flight and the corresponding shower profiles in the electromagnetic calorimeter (EMCal). Neutral pions are reconstructed via  $\pi^0 \rightarrow \gamma\gamma$  decay channel with an invariant mass analysis of  $\gamma$  pairs. An additional energy asymmetry cut,  $|E_{\gamma 1} - E_{\gamma 2}| / (E_{\gamma 1} + E_{\gamma 2}) < 0.8$  is applied to the pairs of photon candidates in the  $\pi^0$  reconstruction. The combinatorial background is estimated and subtracted by mixing pairs from different events with similar centrality, z-vertex position, and event plane orientation. The background is normalized in a region outside the  $\pi^0$  mass peak for each bin in relative angle with respect to the measured event plane direction. A typical signal over background ratio is about 1 to 1 at  $p_T = 3$  GeV/c in midcentral collisions (20–40% centrality). The  $v_2$  of  $\pi^0$  is calculated from the azimuthal distribution after the combinatorial background is subtracted for each centrality and  $p_T$  bin. For the inclusive photon analysis, the charged particle contamination in the sample of the photon candidate cluster is identified by associating the photon candidates with charged particle hits in the pad chamber (PC3) directly in front of the EMCal. The fraction of photon candidates removed by this charge veto cut is about 15–25% depending on centrality. The effect of hadron contamination on the measured  $v_2$  of inclusive photons is estimated by varying the size of the charged particle association window in the PC3, and no significant effect is seen. Neutron and antineutron contamination and off-vertex photons in the identified photon sample are studied with full detector Monte Carlo simulation. The correction for these effects is applied to the data; it is 2% relative to the measured  $v_2$  at 2 GeV/c and negligible at 4 GeV/c. The systematic error includes the effects from the  $\pi^0$  and photon identification cuts and from the event plane determination: 5% for  $\pi^0$  and 5% for photon identification and 5–10% for event plane determination given by the error on the correction factor from the finite event plane resolution. The analysis includes both a minimum-bias sample ( $30 \times 10^6$  events) and a Level 2 trigger sample (equivalent to  $55 \times 10^6$  events), where the Level 2 algorithm is described in Ref. [20].

Figure 1 shows the measured  $v_2$  of  $\pi^0$  and inclusive photons as a function of  $p_T$  for different centrality selections. Data are compared with previous measurements of charged pions [10]. The  $p_T$  and centrality dependences of

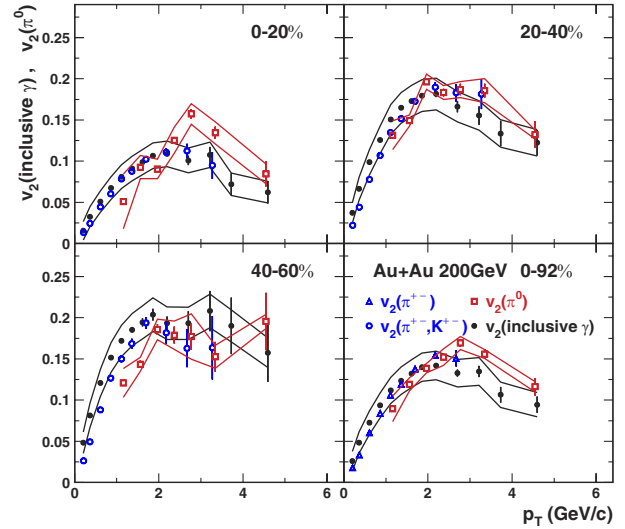


FIG. 1 (color online). The measured  $v_2$  of inclusive photon ( $v_2^{\text{inclusive}\gamma}$ , solid circles) and  $v_2$  of  $\pi^0$  ( $v_2^{\pi^0}$ , open squares) for 4 centrality selections. The statistical (vertical error bars) and systematic errors (lines) are plotted separately. The highest  $p_T$  point corresponds to 4–6 GeV/c. Charged pion data are from previous measurements [10].

both the  $\pi^0$  and the inclusive photon  $v_2$  is consistent with that of other mesons [10]. The  $v_2$  values are significantly above zero up to the highest  $p_T$  points. The nonzero  $v_2$  of  $\pi^0$  up to the highest  $p_T$  cannot be explained by flow effects alone, but may be attributed to jet quenching and/or quark coalescence (recombination).

Figure 2 compares for different centralities the  $v_2$  of inclusive photons with the expected photon  $v_2$  from hadronic decays. The expected photon  $v_2$  from hadronic decays ( $v_2^{\text{bg}}$ ) is calculated by Monte Carlo simulation with the measured  $v_2$  of  $\pi^0$  and other hadronic sources of photon. The relative yield of other sources (mainly  $\eta$ ) is about 20% of the total hadronic decay photons, which corresponds to about 4% relative contribution in  $v_2$  at 1 GeV/c and negligible at 3 GeV/c. In the simulation, we assume that the  $v_2$  of  $\eta$  is similar to the kaon (the closest in mass particle)  $v_2$  measured in [10,11].

The  $v_2$  of the inclusive photons  $v_2^{\text{inclusive}\gamma}$  can be expressed as

$$v_2^{\text{inclusive}\gamma} = \frac{v_2^{\text{direct}\gamma} N_{\text{direct}\gamma} + v_2^{\text{bg}} N_{\text{bg}}}{N_{\text{direct}\gamma} + N_{\text{bg}}}, \quad (2)$$

where  $v_2^{\text{direct}\gamma}$  is the direct photon  $v_2$ ,  $N_{\text{direct}\gamma}$  is the direct photon yield, and  $N_{\text{bg}}$  is the background photon yield. Using the direct photon excess ratio  $R = (N_{\text{direct}\gamma} + N_{\text{bg}}) / N_{\text{bg}}$ , previously measured in Ref. [20], one can express the direct photon  $v_2$  as

$$v_2^{\text{direct}\gamma} = \frac{R v_2^{\text{inclusive}\gamma} - v_2^{\text{bg}}}{R - 1}. \quad (3)$$



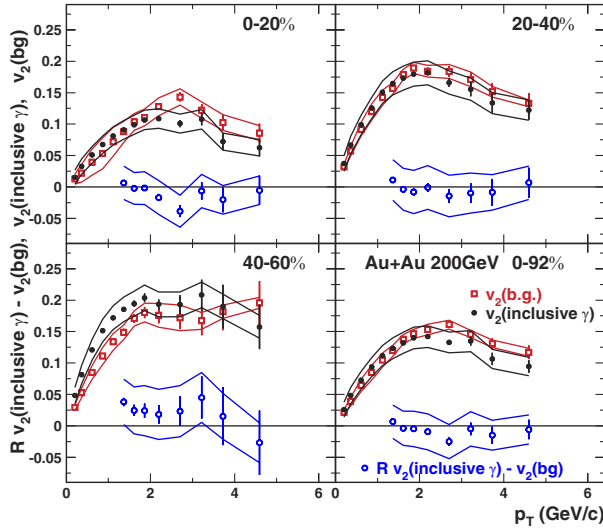


FIG. 2 (color online). The measured  $v_2$  of inclusive photons ( $v_2^{\text{inclusive}\gamma}$ , solid circles) and expected photon  $v_2$  from hadronic decay ( $v_2^{\text{bg}}$ , open squares). A subtracted  $v_2$  quantity  $Rv_2^{\text{inclusive}\gamma} - v_2^{\text{bg}}$  is plotted at the bottom of each panel (open circles), where  $R = (N_{\text{direct}\gamma} + N_{\text{bg}})/N_{\text{bg}}$ . The quantity corresponds to a product of the direct photon  $v_2$  and a positive factor  $R - 1$ , ( $v_2^{\text{direct}\gamma}(R - 1)$ ).

The bottom data points in each panel of Fig. 2 show the difference:  $Rv_2^{\text{inclusive}\gamma} - v_2^{\text{bg}}$  (the numerator in the above equation), which corresponds to a product of the direct photon  $v_2$  times a positive factor  $R - 1$ ,  $v_2^{\text{direct}\gamma}(R - 1)$ . Alternatively, it would be possible to calculate  $v_2^{\text{direct}\gamma}$  using the measured ratio  $R$  [20]. However, we have chosen this subtracted quantity in order to show the direct photon  $v_2$  and its sign, because  $R - 1$  is measured to be small, especially at low  $p_T$ , and is sometimes negative experimentally. The comparison between  $v_2^{\text{inclusive}\gamma}$  and  $v_2^{\text{bg}}$  in each panel indicates that the measured inclusive photon  $v_2$  is consistent with the expected photon  $v_2$  from hadronic decay over the measured  $p_T$  range. The subtracted points are close to zero, which is also expected because of the lack of the direct photon signal in the measured  $p_T$  range, where  $R$  is close to unity [20]. The subtraction is especially meaningful where the measured  $R$  value goes above 1.0 at about 4–6 GeV/c and higher  $p_T$  in central Au + Au collisions [20]; a region where one could extract the direct photon  $v_2$ . The measurement indicates that  $v_2$  of the direct photon is small at least in the highest  $p_T$  (4–6 GeV/c) range in central Au + Au collisions. However, some hidden important trends (slightly negative or positive  $v_2$  of direct photon) as a function of  $p_T$  and centrality could be extracted, once the errors on those two  $v_2$ 's and on the measured  $R$  are small enough. This is because the plotted subtracted quantity needs to be magnified by  $1/(R - 1)$  in order to get the direct photon  $v_2$ . The extracted direct photon  $v_2$  at 4–6 GeV/c is  $-1.5\%$  with  $\pm 6.4\%$  statistical

and  $\pm 6.4\%$  systematic errors for 0–20% central events and  $-2.4\% \pm 6.7\%(\text{sta.}) \pm 9.8\%(\text{sys.})$  for 0–92% (minimum-bias) events.

Figure 3 shows the ratio of  $v_2^{\text{bg}}/v_2^{\text{inclusive}\gamma}$  and a comparison to the measured ratio  $R$  of the yields from [20]. If the direct photon  $v_2$  is assumed to be zero, the ratio  $R$  should be equal to  $v_2^{\text{bg}}/v_2^{\text{inclusive}\gamma}$  according to the Eq. (3). If the measured direct photon excess comes from the initial hard scattering, that would correspond to zero  $v_2^{\text{direct}\gamma}$ , then the measured  $v_2$  ratio  $v_2^{\text{bg}}/v_2^{\text{inclusive}\gamma}$  gives a consistent check of the direct photon excess ratio  $R$  measurement, especially where  $R$  is significantly above 1.0. The measured  $v_2$  ratio as a function of  $p_T$  and centrality is consistent with the conventional relative yield measurement of the direct photon excess ratio  $R$ , but has somewhat larger errors.

In conclusion, the  $v_2$  of identified  $\pi^0$  and inclusive photons as a function of  $p_T$  and centrality are measured with the PHENIX central arm spectrometer at  $|\eta| < 0.35$  with respect to the event plane defined at  $|\eta| = 3.1 \sim 3.9$  in 200 GeV Au + Au collisions at RHIC. The  $v_2$  of identified  $\pi^0$  shows a similar trend as a function of  $p_T$  and centrality compared with other mesons and has values significantly above zero up to the highest  $p_T$  point. The measured  $v_2$  of the inclusive photons is consistent with the  $v_2$  of photons from hadronic decays, which is furthermore consistent with the absence of direct photon signal over the measured  $p_T$  range. However, the measurement indicates a small direct photon  $v_2$  for the highest  $p_T$  (4–6 GeV/c) range in central Au + Au collisions. The ratio of the estimated photon  $v_2$  from the hadronic decay over the measured inclusive photon  $v_2$  is also consistent with the

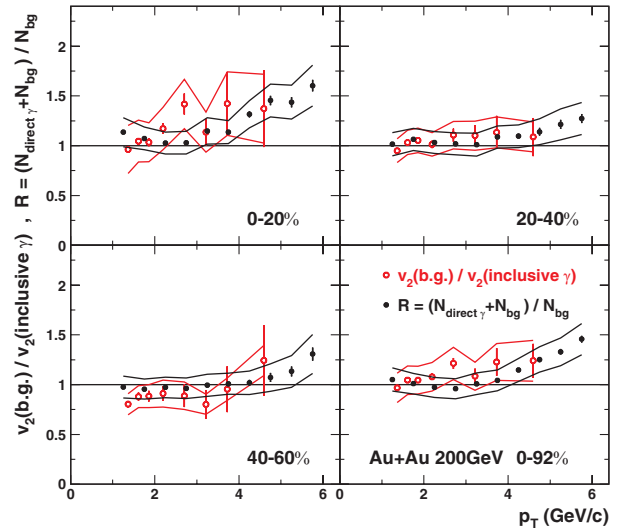


FIG. 3 (color online). The ratio of the hadronic decay photon  $v_2$  over inclusive photon  $v_2$  ( $v_2^{\text{bg}}/v_2^{\text{inclusive}\gamma}$ , open circles) compared with the direct photon excess ratio  $R = (N_{\text{direct}\gamma} + N_{\text{bg}})/N_{\text{bg}}$  (solid circles).

direct photon excess ratio measured via conventional yields ratio. This should also imply that the  $v_2$  of direct photons is zero where the measured direct photon excess ratio  $R$  is significantly above 1.0. The present statistics and systematic accuracy of the data from the second year of RHIC running do not allow us to explicitly state the magnitude of direct photon  $v_2$ . However, the indication of small  $v_2$  for direct photons would favor the naive scenario of direct photon production from initial hard scattering and its small interaction with produced matter in high-energy Au + Au collisions.

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\*Deceased.

†Email address: zajc@nevis.columbia.edu

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